International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249-6890; ISSN (E): 2249-8001
Vol. 8, Issue 3, Jun 2018, 791-802

MODERN PLANT MAINTENANCE AND RELIABILITY MANAGEMENT METHODS – A REVIEW

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ABSTRACT

The period from the 1990s has seen a large body of work in the areas of Plant Maintenance and Reliability Management. While strategies like RCM and TPM are popular and well known, there is also a large body of work that has attempted to move forward from these methodologies. The main intent of these approaches has been to address the issues faced during implementation of these methods. The newer methods of Plant Maintenance and Reliability Management are not as well known as the conventional methods. This paper attempts to collate and organize this body of knowledge in the form of a comprehensive review.

KEYWORDS: Maintenance, RCM, Reliability & A-RCM

Received: Apr 16, 2018; **Accepted:** May 10, 2018; **Published:** Jun 01, 2018; **Paper Id.:** IJMPERDJUN201883

INTRODUCTION

Maintenance was an area that was often thought of an area that did not need much attention. However, with the greater focus on safety, environment, energy efficiency and profitability Maintenance has now become an area where there is renewed attention. Maintenance in the past was thought in terms of Breakdown and Preventive Maintenance. Starting from the late eighties and early nineties, there have major developments in Maintenance. The advent of Predictive and Condition Based Maintenance resulted in major improvement to equipment life and consequently to the overall reliability of equipment. The wider appeal of strategies like Total Productive Maintenance (TPM), World Class Manufacturing (WCM)and Six-Sigma also saw an increased focus on Plant Maintenance.

In addition to Plant Maintenance, Reliability Management also has gained prominence, wherein the focus has shifted to not just attending to plant and machinery, but to manage equipment as an interconnected system under a larger umbrella of Asset Management. The emergence of Reliability Centered Maintenance (RCM) in the Airline Industry and the demonstrated improvement in the reliability of the assets has resulted in a closer focus on Reliability Management. Currently, Plant Maintenance and Reliability Management go together and are thought of as not two separate streams but as one integrated method.

This interest in Plant Maintenance and Reliability has resulted in many tools, methods and strategies proposed by the various researchers, consultants and industry professionals. This large body of work is presently under varied sources of Engineering and Management. This paper attempts to collate the more relevant works in

A Review

one place to serve as a reference to researchers and professionals.

LITERATURE SEARCH METHODOLOGY

The first step in a Literature Review is to carry out a deep search of the published works in the relevant areas. To identify the relevant resources a search primarily using Google Scholar was conducted. The search was carried out by a two-step process. Search terms like ‘Maintenance Strategy’, ‘Preventive Maintenance’, ‘RCM’, ‘Condition Based Maintenance’, ‘TPM’, ‘Reliability Management’, “Maintenance Optimisation”, “Maintenance Models” and other relevant keywords were used for the search. From the works obtained from these searches, further linkages were obtained from the references in those papers and those papers were studied.

ORGANISATION OF REVIEW

As detailed earlier, TPM, RCM, WCM and Six-Sigma can be thought of as the starting point of the interest in Plant Maintenance and Reliability Management. These are popular and well known to researchers and professionals. Hence, these two core methods are not detailed here. Considering that TPM and RCM have limitations in implementation, it is natural that there are alternatives proposed to these methods. However, it was observed that there are several alternatives proposed to RCM while hardly any alternatives to TPM or Six-Sigma have been proposed. The aim of the alternatives and strategies were to provide a simpler means of implementation. Considering the wide variety in the methods, a logical grouping of the methods is essential for better understanding. These areas below:

- Mix of Approaches
- Simplification of Analysis
- Optimization Methods
- Broad Strategies
- Mathematical Models

While the primary purpose of this paper is to present a detailing of the various strategies for the reference of the researchers and practicing professionals, a brief analysis of the strategies is also provided along with the authors’ conclusion on the relative merits and demerits of these strategies.

MIX OF APPROACHES

A common approach followed by practitioners in the industry is that of following different approaches. This section highlights some of these approaches.

Bloom (2005) has put forth an alternate approach to the RCM implementation process. Here the approach centers on the Consequence of Failure Analysis (COFA) as the guiding point. He describes the alternate process steps as follows: “1) Describing the component functions (where all functions of the equipment are defined, 2) Describe the functional failures (against each of the functional failures) 3) Describe dominant component failure mode for each function failure (where only plausible and realistic failure modes are included) 4) Assess whether the occurrence of the failure mode is evident (by this he means whether the failure of the component can be made evident by a control or detection system) 5) Describe the system effect for each failure mode (wherein the effect, functional statutory, safety etc. are listed) 6) Describe

consequence of the failure based on the asset reliability criteria 7) Defining component classification (where the final decision has to be entered into as critical or run to failure)" [1].

Mokashi et al (2002) report that "there are other approaches, which cannot be called RCM but are based on the same principles and have delivered positive results. One such approach is risk-centered maintenance or Risk-CM. NASA has in its RCM guide said that one of the primary principles of RCM is that RCM uses the logic tree to screen maintenance tasks, that is, it uses broad categories of consequences of failure to prioritize failure modes. However, Risk-CM uses a combination of probability and consequence, that is, a risk to prioritize failure modes" [2].

Jones (1995) puts forward Risk-Based Reliability Centered Maintenance (RBCM), a new variance of basic RCM. Basically, RBCM can be described as RCM, but with a strong statistical background. This tackles and eliminates the drawback of the ad hoc FMEA of the traditional RCM approach. Risk-based inspections (RBI) are one of the core concepts here. The RBI methodology enables the assessment of the likelihood and potential consequences of pressure equipment failures. RBI provides companies with the opportunity to prioritize equipment inspections and optimize the inspection methods, frequencies and resources. Furthermore, RBI helps to develop specific equipment inspection plans and enable the implementation of RCM as such. This results in improved safety, lower failure risks, fewer forced shutdowns, and reduced operational costs. The risk-based approach requires a systematic and integrated use of expertise from the different disciplines that affect plant integrity. These include design, materials selection, operating parameters and scenarios, and understanding of the current and future degradation mechanisms and of the risks involved" [3].

Kelly (1997) developed a Business-Centered Maintenance (BCM), a concept for determining a detailed maintenance plan. Kelly emphasized the importance of identifying, mapping and auditing the maintenance function. The BCM concept also pays attention to the necessary administrative support. Kelly calls his approach a BUTD approach, bottom-up/top-down approach. "First, it is a top-down, step that starting from the business context, the exact objectives for maintenance are outlined considering all corporate level. The second step is a bottom-up step. It aims at establishing a life maintenance plan for all equipment. In a third and last step, all item life plans are fitted in a maintenance strategy" [4].

Selvik and Aven (2011) introduce the concept of uncertainty as opposed to probability and state "the traditional RCM approach can be viewed as founded on a risk perspective where risk is equal to the expected value or the combination of probabilities and events/losses. They state that in order to consider the uncertainties, RCM needs to be based on a broader risk perspective by substituting probability with uncertainty in the definition of risk" [5]. They further introduce a new model known as RRCM, which is "a framework based on the existing RCM, which improves the risk and uncertainty assessments by adding some additional features to the existing RCM methodology" [5].

Selvik and Aven (2011) also report that the method suggested has methods to address uncertainties ''hidden'' in the assumptions of the standard RCM analyses. The uncertainties are then reported to management. The report integrates the results from the FMECA and the uncertainty analysis. An essential feature of the presented framework is the managerial review and judgment, which places the decision process into a broader management context. In this step, consideration is given to the boundaries and limitations of the tools used [5].

Khan and Haddara (2004) reported on a methodology, called risk-based maintenance (RBM). This they report is based on a mix of Risk and reliability. The most likely failures are evaluated, then the most probable ones are selected for which more detailed study is done. A consequence or impact analysis is also done. Finally, a consolidated risk number is

generated which then is used for failure prioritization [6].

Prabata and Wiyana (2012) presented a case where RCM and RBI methodology were applied together on a compressor [7]. This was on a single equipment and they did not extend this further.

Abid, et.al. (2014) presented an alternative approach to RCM "in which RCM is integrated with life data analysis in order to accurately estimate the failure mode followed by each component of the system". They state that "using this technique a better failure management policy is developed keeping in view the health of each equipment. This RCM plan helps to optimize reliability of the system while being cost-effective and decreasing the system downtime" [8].

SIMPLIFICATION OF ANALYSIS

This section describes alternatives that rely primarily on simplification of approach by eliminating one or more steps.

Endrenyi et al (2001) also described an alternate approach to RCM called Preventive Maintenance Optimization (PREMO). They describe this as based on "task analysis rather than on system analysis. This approach is claimed to have the capability of drastically reducing the number of maintenance tasks" [9].

Mokashi et.al. (2002) report about a method called PMO2000 in which the failure modes are identified by analyzing the maintenance tasks. This method looks at the task to identify failure modes. It can be considered as a bottom-up approach at direct variance with FMEA which is top-down [2]

Bevilacqua and Braglia (2000), refer to a case where the internal methodology developed by the company to solve the maintenance strategy selection problem for the new IGCC plant is based on a "criticality analysis" which may be considered as an extension of the FMECA technique. This analysis considers the following seven parameters:

- Machine criticality
- Operating conditions
- Maintenance costs
- Safety
- Failure frequency
- Downtime length
- Machine maintenance ease [10]

Zajicek and Kamenicky (2007), proposed a methodology to improve the effectiveness of RCM. This method prescribed on a) Better team time organization b) Use of standardized Maintenance Plans and c) Analysis of only selected components [11].

Wattum (2014) provided an alternative that a solution for implementation of RCM in organizations could perhaps simply be to emphasize more on the living program than the initial analysis. "Splitting the analysis in smaller sub-analyses allocated with one facilitator for those who have responsibility for the system under review, would involve no big analysis to be performed at once. Rather, many smaller analyses would be performed with the same facilitator with those who work on the equipment. Such an approach would not feel time-consuming in the same way if the process was limited to demand

less than one day per analysis. If the analysis would be several times with appropriate intervals, one would have gathered information from direct sources on how each system functions that would prepare for high quality in the analyses. This could increase the appreciation of RCM, accuracy of the assessment, and lower the impression of the analysis being resource demanding" [12].

OPTIMIZATION METHODS

Another alternative approach is that of Maintenance optimization. This has been described in detail by Dekker and Scarf (1998), Turner (2002), Berger (2005), Idhammer (2008) and Dotzlaf (2009).

Maintenance optimization is a practice that uses mathematical models to assist with the decision-making process for maintenance implementation. These models combine reliability with economics by quantifying costs, benefits, and various constraints, and integrating the factors into basic economic methods. These models are particularly helpful for comparing the cost-effectiveness of different maintenance policies, determining efficient inspection and maintenance frequencies, and incorporating numerous constraints into the decision-making process (Dekker, 1996) [13] [14]. The traditional optimization model provides a simple, easy to understand example of how optimization models work [15], [16]. While the most useful models will optimize for multiple criteria, the traditional model only optimizes for one variable – cost as per Dotzlaf (2009) [17].

The traditional model is very helpful in understanding the concept of maintenance optimization; however, it is not as practical in realistic applications for two reasons: it optimizes for only one variable and failure trends are rarely accurate. The optimal maintenance frequency can vary depending on the variable being optimized; since the traditional model only optimizes for one variable, it could lead to incorrect conclusions and poor decisions for maintenance scheduling as per Berger (2005) [15]. Idhammer (2008) points out that since components rarely fail after a predictable time, it is very difficult to accurately depict equipment failure trends [16].

The models have the advantage that these provide a quantitative approach for identifying the most efficient balance of resource expenditures and maintenance benefits [14]. Turner states that, when analysis reveals no optimal solution, these models help determine candidates for reactive maintenance and the tasks to be eliminated [18]. Similarly, these models can help identify which systems could be more efficiently managed by simpler or more advanced technology. During development, optimization models help users understand how to predict equipment life more accurately, which data to collect, and how to assess the level of risk for a given maintenance frequency [16], [18]. While maintenance optimization models have obvious benefits, there are a lot of difficulties in the application that can make the benefits hard to realize. These difficulties are among the numerous disadvantages of maintenance optimization models. Maintenance optimization models require massive amounts of performance and failure data that is often hard to obtain; maintenance craftsman may have significant knowledge about these aspects of the equipment, although it is often difficult to translate this knowledge into data [14]. When data is available, optimization requires a lot of detailed calculations that can be time-consuming, hard to standardize, and difficult to validate. Further yet, the results of these calculations are rarely useful because a large amount of guesswork must be used to compensate for missing data or lack of expert knowledge [18]. Optimization calculations require the user to quantify all factors, to include the benefits of maintenance; however, many of the necessary factors are very subjective in nature and difficult to quantify [14]. Therefore, implementing an optimization model for an entire maintenance program with numerous pieces of equipment and systems is rarely feasible; the common trade-off, which often leads to suboptimal outcomes, is a simplified approach that does not consider all factors (Vatn, et.al.,

1996) [19].

Besnard et.al. (2010) report on the Quantitative Maintenance Optimization (QMO) techniques as that they are "are characterized by the utilization of mathematical models which quantify both, the cost and the benefit of maintenance and determine an optimum balance between these. The task in QMO is often to find the minimum total cost consisting of:

- The direct maintenance costs, e.g. for labor, materials and administration, which increases with the intensity of maintenance actions, and
- The costs resulting from not performing maintenance as required, i.e. due to loss of production and due to additional labor and materials after component breakdowns [20].

BROAD STRATEGIES

In addition to these approaches, there are broad strategies that encompass the entire maintenance umbrella and can be used as stand-alone alternatives to RCM unlike other approaches described in the preceding sections. This section describes the few such alternatives developed.

Bae, et.al. (2009), proposed an alternative algorithm to RCM. The proposed RCM Planning Method comprises two steps. The first step uses the reliability matrix to minimize the total maintenance cost while, at the same time, maximize the subsystem reliability. This is achieved by using a multi-objective optimization method. From this, the maintenance cost function can reflect the current maintenance characteristics of the components by generating essential cost factors defined by the reliability, and maintainability, of each component. This method which was more mathematical and model building in nature, defines the reliability function of the system by using a reliability network, between appropriate subsystems and components, which mimic an artificial neural network. The second optimization step allocates the maintenance reliability of each component to the maintenance cost, reliability function, and desired subsystem reliability. In the case of maintenance reliability allocation, the optimization process seeks to minimize the maintenance costs whilst meeting the desired subsystem reliability requirements. This research applies an algorithm to find the best reliability allocation by optimization. Finally, they presented a maintenance plan, determined by estimating the maintenance time of the components as derived from the allocated reliability, and reliability indexes, in the inverse analysis of the fundamental reliability function [21].

Waeyenbergh and Pintelon (2002) developed a model called the CIB model which is also a 7-step process consisting of the following steps:

Step 1: Identification of the objectives and resources. Step 2: Selection of the MISs (Most Important Systems), Step 3: Identification of the MCCs (Most Critical Components), Step 4: Maintenance policy selection, Step 5: Optimization of the maintenance policy parameters. Step 6: Implementation and evaluation, Step 7: Feedback [22]

Cheng et.al. (2008) presented an alternative to RCM called the Intelligent RCM Analysis (IRCMA) as in the figure. This approach focuses more on the use of an 'intelligent' system. As it provides approaches that are generic in nature, it is being classified as a broad strategy [23].

Besnard et.al. (2010) reported about the existence of a strategy called the Reliability-Centered Asset Maintenance approach (RCAM) which "is a quantitative approach of RCM relating preventive maintenance of equipment to system reliability and total cost. It merges the concepts of RCM and QMO and is claimed to overcome the drawbacks of the two

separate approaches.

The RCAM approach is a structured method originally developed for a combined analysis of reliability, maintenance, and life-cycle cost of power systems” [20].

The three stages of the RCAM approach are - System reliability analysis, Component reliability modeling and System reliability and cost/benefit analysis [20].

Ahmadi et.al. (2010) described an alternative to RCM called MSG-3 [24]. The process, while being closely related to RCM, has some differences in their approach for analyzing maintenance tasks.

Barbera et. al. (2012) presented an advanced model for the integral maintenance management in a cycle of continuous improvement, which is aligned with the strategies, policies and key business indicators. This model claims to use a series of real aspects (not covered in other models) needed to convert a theoretical model in a real and useful maintenance management model. Thus, the model claims to consider the real or genuine constraints that could limit the design of preventive maintenance plans and the resources to do so. It considers the selection of critical spare parts (inventory cost vs. cost due to unavailability of critical equipment) and the positive involvement of e-technologies (e-maintenance) in modern maintenance management on a global level. In turn, the model consists of seven arranged stages that follow a logical sequence of action hierarchy and align local maintenance objectives with the global business objectives; all these in a framework for continuous improvement using the principles of the BSC methodology applied to maintenance management.

The stages defined in this area:

- Analysis of current situation
- Ranking of equipment
- Analyzing weakness in the equipment
- Design of maintenance plans
- Maintenance scheduling and optimization
- Control and evaluation
- Life cycle analysis and replacement [25]

Accelerated Reliability Centered Maintenance is a maintenance management strategy that was conceptualized in Mangalore refinery and Petrochemicals Ltd. The concept was first presented in 2007 (Prabhakar et.al., 2007) [26]. The strategy was further developed, and greater maturity was brought in and the final form of A-RCM was described by Prabhakar and Raj [27].

A-RCM is a four-stage process. The strategy has been conceptualized as a four-stage process so that the benefits begin to accrue as soon as the first stage is completed. The first stage is the Reliability Audit stage and details essentially consist of the following steps:

- Carry out reliability audits
- List equipment wise failure modes

- Compulsorily apply the root cause failure actions to standby equipment
- Identify most frequently occurring failures and address these immediately
- Identify bad-actors based on the lowest MTBF
- Identify actions for these bad actors

At the end of this stage, the strategy yields the first cut maintenance tasks – preventive, predictive and design change that RCM yields after the completion of the final stage. This is not the final list of tasks to be done, but rather a quick-win set of activities. Typically, in an organization that has a PdM program as well as an RCFA would find it easy to implement the first stage. In the case of an Indian petroleum or Petrochemical organization, this would be the minimum requirement as stipulated by the OISD standards. As the identification of tasks happens quickly, the improvement in reliability is seen at this stage.

The second stage is where the identification of likely failure modes take place. In this stage, equipment are grouped based on commonalities – based on make and model, based on similarity of service and based on similarity of construction. Here the tasks that were identified for a particular asset is applied to all similar assets. This leads to a quick scaling up of the maintenance task selection and application. This step results in the prevention of failure that has not happened yet but has a higher likelihood of occurrence. This step provides a more optimized task selection methodology than traditional FMEA based task selection that the classical RCM uses. This stage is where the highest improvement in reliability is seen. The third stage carries out FMEA for Critical Equipment. This again increases the probability of failure being prevented by a deliberate action. This stage is kept to the 3rd because, although the equipment are critical in nature, the very criticality results in in-built reliability and robust design.

Dharmaraj & Prabhakar (2017) have evaluated the performance of A-RCM and indicates that there is significant benefit obtained by the reporting organization [28]

Yu et.al. (2016), reported an improved methodology of RCM called RtCM which combined the optimization techniques with RCM to generate a new technique in a Nuclear Plant. This primarily dealt with strengthening the analysis of failures and also the efficiency improvement of the overall RCM process [29].

MATHEMATICAL MODELS

There have been many attempts to provide one-off models of RCM that are predominantly mathematical in nature and rely on probabilistic approaches to the RCM. These models focus on a specific aspect of the RCM rather than as a comprehensive implementable strategy. These models have largely been based on Markov methods.

Endrenyi et.al. (1998) presented a model that measured the impact of maintenance on reliability [30]. Theil (2005) presented an extension of the Markov-model of this method in application to RCM. In this model, to include exploitation-time dependent outage rates, the time-behavior is approached by a step-by-step trend function. In that way, to each wear-out state, a special outage rate is assigned. Thiel concluded that “because of its complexity the direct implementation of the proposed model is not applicable in practice. However, he states that by neglecting state transitions, the complex model can be reduced and thus be implemented into conventional reliability calculation software without major modifications” [31].

Croacker and Kumar (2000) proposed an alternative to RCM – Age-Related Replacement based on Hard-life and Soft-life and proposed a model for suggesting replacement intervals. By their own admission, the example they showed took about 10 hours to produce the output, using a full grid search for just one part [32].

Adoghe (2010) developed a Markovian model to assess the effect of RCM implementation which strictly is not a new model but a new method of assessment [33].

Aurich et.al. (2006) proposed the Quality Oriented Analysis. The analysis procedure assesses the cause-and-effect coherences between the condition states of machines as well as tools and the product quality within manufacturing process chains. Thereby, the procedure consists of a deductive and an inductive analysis phase. During deductive analysis, the manufacturing process chain and inherent cause-and-effect coherences are identified and documented. Structure models of the manufacturing process chain and more or less established hypotheses about cause-and-effect coherences are the provided results. Following, during the inductive analysis, the identified hypotheses are verified or falsified based on the empirical analysis of data collected within manufacturing process chains [34].

Sikos (2010) proposed a new model that considers the interaction between maintenance cost and the reliability index [35]. Here the 'time-dependent reliability index as proposed earlier by Neves et.al. (2004) is used [36]. Laasko and Simola (1998) described a model based on indicators and developed a decision criteria model [37].

In addition to these a number of models were presented across the years were also presented as follows:

System of complete Maintenance indicators [38], Quantitative techniques for Maintenance Management, Expert Systems [39], Effectiveness & Efficiency of Maintenance [40], Integrated approach using situational management theory [41], Feedback control based on concepts of SQC [42], Sharing of Maintenance information across platforms [43], e-Maintenance [44], Outsourcing convenience as a decision driver [22], Union of tools like QFD & TPM [45], External stakeholder impact [46], Improvement of Operational reliability & Life Cycle cost [47] and Component Replacement decision models [48].

LEARNINGS FROM REVIEW

The review highlighted close to fifty different Plant Maintenance and Reliability Management methods. While only a summary of the method was provided here, it is pertinent to note certain observations on these methods. The large body of work detailed here indicates that there is a major change in the was Maintenance is perceived.

The research attention is a pointer to the fact that an area that was often relegated to the sidelines is now being mainstreamed. Perusing all the various methods suggested, the authors find that there is a limited amount of research and publication happening on broad strategies. TPM and RCM remain as preferred strategies for implementation. While it is observed that the body of research modifying TPM is virtually non-existent, there is a large body of work that is attempting to modify the RCM methodology. All work that attempts to modify RCM state explicitly that RCM as a methodology has definite advantages but have inherent difficulties in implementation which served as the motivation for the researchers to attempt these modifications.

The review also indicated that there is a large body of work attempting to approach Reliability Management through mathematical models. It was observed that these models remain one-off works with limited follow-on works or adaptations, as opposed to non-mathematical based works which find greater applications in the industry. This serves as a

pointer too to researchers that works that are broader with limited mathematical rigor will find the greater application and will result in better adoption for implementation by the practitioners.

CONCLUSIONS

This paper attempted to provide a reasonable compendium of Plant Maintenance and Reliability Management methods beyond those that are well known and popular. While an attempt has been made to cover a large number of methods here, this paper is by no means claimed as a complete compendium of the body of knowledge on Plant Maintenance and Reliability Management but rather is attempted as a potential starting point for researchers in this area. It is expected that the works referred here, along with the citations in those papers open up vast resources for the researchers who will be working in the field of Plant Maintenance and Reliability.

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